Proceedings of the Institute of Acoustics

CALIBRATION AT HIGH POWER OF PULSED ACOUSTIC TRANSDUCERS

R.A.Hazelwood

Aconics Partners, Guildford

Introduction

When acoustic transducers are to be used at high power levels, extra measurements are required. At low levels it is usually safe to assume that the transducer is linear, with properties that are independent of power level, but as the stresses increase this is often no longer true.

Piezoelectric transducers present a reactive load to the power amplifier. A standard measurement technique plots the real and imaginary admittances (conductance G and susceptance B), at low power levels. These values can be used to assess the electrical power requirements, and to design appropriate matching circuitry. However, if the transducer is not linear, these predictions are no longer valid and it is necessary to make appropriate measurements at the power level at which the transducer is expected to operate. These results can be used to optimise the matching networks and power amplifier for the most critical condition of peak power output.

As well as being power level dependent, the transducer's characteristics will often be time dependent, as it gets hot or the nature of the mechanical load varies. It is then necessary to be able to make measurements quickly, and preferably on a few cycles only. Recent developments in digital storage oscilloscopes have made this otherwise very difficult task much easier.

Prediction of failure modes

Piezoelectric transducers can fail in several different ways, which depend on their design. Although capable of producing very efficient high power transducers piezoelectric ceramics are brittle. Failure by splitting under tension happens at relatively low power, and without warning. This mode of failure can be overcome by prestressing the ceramic either by clamping it between metal parts (the composite piston type of transducer) or gluing pretensioned fibres around it ("fibreglass" reinforced tubes). These techniques also prevent failure of the bond of the electrode to the ceramic.

Failure of prestressed transducers is more complicated, but is usually associated with the increased losses, both dielectric and mechanical which occur at the higher stress levels[1]. This leads to heating, which causes large changes in the ceramic properties, and can lead to a permanent loss of the polarization in conjunction with the high stress levels. However, there are reversible changes which occur first, and where these can be monitored they provide an indicator of impending failure.

CALIBRATION AT HIGH POWER OF PULSED ACOUSTIC TRANSDUCERS

Application to underwater projectors

Transducers for underwater sound projection often operate at high peak power level but for very short pulses. Pulse lengths are typically a few milliseconds, and to further reduce the mean power consumption, the repetition rate is often kept low. These low duty cycles are also useful to allow the reverberation and multipath transmission intensities to die down before the next pulse. However this makes the electrical measurements more difficult because the necessary phase sensitive systems require many cycles to stabilise.

Typical calibration arrangements can provide even tighter limits on the available pulse lengths, because of the limited size of the water volume available to absorb the sound. Gating of the received signal over a 1 millisecond period allows accurate measurements to be made in small tanks, in which the water depth is greater than about 2 metres. This means that small transducers whose far-field starts at less than 1 metre range can be assessed before the first echo arrives from the tank wall or the water surface. The input signal must then also be gated to allow the reverberation to die down, and the two gating controls co-ordinated to optimise the receive period.

Calibration of linear underwater transducers

Calibration of linear transducers can be made using a combination of pulsed measurements and CW (continuous wave) measurements. For an acoustic projector the most commonly quoted data is the projector voltage sensitivity, S_v. This is the ratio of the acoustic pressure, P_1, at a standard distance of 1 metre, to the applied voltage. This is most simply specified in SI units of pascal metres per volt (Pa*m/V).[2] It can then be converted to the commonly used decibel value referred to micropascals/volt at 1 metre (dB//μPa/V @1m).

Measurement of this sensitivity can be made without any phase information being required. A calibrated hydrophone is necessary, placed at range R, whose receive sensitivity, M_v, can be quoted in V/Pa, or the corresponding decibel value in dB//V/μPa. The input voltage applied to the projector V_p, and the voltage received from the hydrophone, V_H, can be measured with a calibrated oscilloscope, and the sensitivity calculated

$$S_v = \frac{V_H * R}{V_p * M_v}$$

In making these measurements several conditions need to be observed, including

1. The input impedance of the voltmeter or oscilloscope used for measuring V_H needs to be sufficiently high not to load the hydrophone. Any reduction in M_v due to loading by the input capacitance of the voltmeter or additional test cable, must be assessed and the calculation adjusted. For sinusoidal outputs, either peak to peak (p/p), or root mean square (rms) values can be used provided this choice is consistent. For measurements taken from an oscilloscope screen p/p are the most appropriate, but in this discussion rms values will be used as it is then simpler to relate the voltages to power levels.

2. Thus the input voltage, V_P, will be considered to be the rms value, measured at the end of the transducer cable (see the figure). An underwater transducer, of necessity, has an integral cable, at least during calibration. This cable can be considered as part of the device, so that no compensation to the electrical or electro-acoustic parameters (such as M_v), will be required unless the length of cable needs to be changed.

3. The hydrophone is placed at a range of R metres, chosen to avoid problems of echoes and reverberation, and to place it in the far-field of the projector and it's housing. This means that the acoustic wavefront is substantially spherical, and the projector can be considered as a point source. The range is then measured from this point, the "acoustic centre". The acoustic pressure measured on the spherical surface (radius R) will vary with direction, but it's dependence on R will follow the spherical spreading law.

With the above conditions satisfied the rms pressure, P_R, is inversely proportional to R, and acoustic intensity is given by

$$U = \frac{P_R^2}{d*c} = \frac{P_1^2}{R^2*d*c} = \frac{S_v^2*V_P^2}{R^2*d*c} \quad \text{watts/m}^2$$

where d is the density of water (kg/m³)
c is the speed of sound in water (m/s)

The projector sensitivity S_v, used above, is the response to voltage. If the admittance, Y, is known, S_v can be converted to the current sensitivity, S_I, in units of Pa*m/Amp. This second parameter is useful because it can be used to calculate the receive sensitivity, M_v. For piezoelectric transducers made with passive parts and no active electronics, the acoustic reciprocity principle can be used [3,4]. This gives the following relationship under the conditions of far-field spherical spreading-

$$M_v = \frac{2*S_I}{d*f} = \frac{2*S_v}{Y*d*f}$$

where f is the frequency in Hz. Thus S_v, S_I, and M_v are determined.

CALIBRATION AT HIGH OF PULSED ACOUSTIC TRANSDUCERS

The last parameter required for the calibration of a linear reciprocal transducer is the electro-acoustic efficiency, E. This is the ratio of the total acoustic power radiated to the electrical power absorbed. For an omnidirectional transducer where the sensitivities are independent of direction this can be calculated if the conductance, G, is known. The electrical power absorbed from a sinusoidal signal, W_E, is given by

$$W_E = V_P^2 * G$$

The acoustic power radiated, W_A, is then given by the area integral of the intensity over a sphere radius R

$$W_A = \int U \, dA = U*4\pi R^2 = \frac{4\pi*S_V^2*V_P^2}{d*c}$$

This can be generalised for non omnidirectional transducers by using a directivity factor Df, the ratio of U_N, the intensity in the direction of interest, to the mean intensity over the sphere

$$Df = U_N / \int \frac{U}{4\pi} \, dA$$

Df can be measured by rotating the projector and integrating the results as above. In practice, the transducer symmetry can be used to minimise these measurements. The acoustic power now becomes

$$W_A = \frac{U_N*4\pi R^2}{Df} = \frac{4\pi*S_V^2*V_P^2}{Df*d*c}$$

As expected, with the assumptions of spherical spreading this power is independent of range R. The efficiency can now be calculated

$$E = \frac{4\pi*S_V^2}{Df*d*c*G}$$

The far field performance of a linear reciprocal transducer is then fully characterised by knowledge of V_P, V_N, Df, Y, and G at each frequency.

High power pulse measurements

Measurement of V_P, V_N, Df and Y, even with short pulses, is not difficult, because no phase information is required. In contrast, whilst G and B can be measured for CW signals using readily available instrumentation, pulsed signals present more difficulty. However, recently available digital storage oscilloscopes have facilities to multiply two waveforms together and take the average over a defined period. If one channel is set up to measure voltage and the other current a VI product waveform is produced. This VI product represents the instantaneous power dissipation. If averaged over a whole number of cycles the mean power value, W_E, is obtained.

If the phase angle ,ϕ, is referred to the real axis, then

$$G = Y*\cos\phi \qquad B = Y*\sin\phi$$

Thus the power absorbed W_E, is given by

$$W_E = V_P^2*Y*\cos\phi = VI$$

The mean VI value can now be used to calculate efficiency, the power factor cosϕ, and the effective values for B and G. Knowledge of the susceptance B gives the equivalent capacity and the inductance required to properly match the transducer to the power amplifier.

Using a multiplying oscilloscope
This alternative scheme measures V_P, V_T, and Dt as before, but measures I_P, the projector current, and VI, the average power absorption, in place of B and G. Figure 1 shows the circuit requirements. I_P is most conveniently measured using a probe based on a current transformer, which can be clipped over one of the wires to the transducer. However, such probes are not always available, and it is possible to measure the voltage developed across a series resistor with little error. The value of this resistor will need to be adjusted for different transducer impedances, but in practice 10 ohms is a useful starting point. This needs to be fitted in the 0 volt line because the two oscilloscope probes must have a common ground point. The transducer then "floats" a few volts away from this ground. This is only acceptable for transducers insulated from "earth" (the water in this case). If this is not so a current transformer probe will be required.

Choosing the gating period
It is important when using time average representations of signals to consider the effects of the gating period. As will be shown, even for unmodulated sinusoids the rms values will be in error unless the gate period over which the waveform is averaged is an exact number of half cycles. While this can achieved if the gate period is recalculated for each frequency, it is simpler to use a fixed period , or one chosen primarily to avoid the problems of reverberation and spurious harmonics generated near the pulse envelope edges. In this case the error will be minimised by increasing the length of the sample.

The most critical measurement is found to be the mean power VI. The current and voltage waveforms can be written as folllows-

$$V_P(t) = V_0\sin(wt) \qquad I_P(t) = I_0\sin(wt + \phi)$$

where w is the angular frequency in radians/sec
and ϕ is the phase angle in radians

CALIBRATION AT HIGH POWER OF PULSED ACOUSTIC TRANSDUCERS

The power absorbed is then

$$VI(t) = \frac{V_o * I_o}{2} * (\cos\phi - \cos(2wt + \phi))$$

where the product of sines has been converted into a more convenient form. It shows that unless $\cos\phi = 1$ there are moments when the instantaneous power consumption is negative! This feature is indeed seen on the VI(t) waveforms seen in practice, which as shown above consist of a DC term $V_o I_o \cos\phi/2$ plus an oscillatory term with twice the frequency of the input voltage. Clearly the mean power over any number of half cycles will be positive as the oscillatory term is then zero.

The rms values of $V_p(t)$ and $I_p(t)$ can be calculated by a similar analysis to give

$$V_p = V_o/\sqrt{2} \qquad I_p = I_o/\sqrt{2}$$

Thus these three measurements V_p, I_p, and VI give the power factor and admittance, from which conductance and efficiency are found

$$\cos\phi = \frac{VI}{V_p * I_p} \qquad Y = \frac{I_p}{V_p} \qquad G = \frac{VI}{V_p^2} \qquad E = \frac{4\pi * S_v^2 * V_p^2}{Df * d * c * VI}$$

To calculate the error due to the averaging period δt not being an integral number of half cycles the second term in VI(t) has to be integrated from time t to t+δt, and divided by δt to give

$$Err = \frac{V_o * I_o}{4 * w * \delta t} * (\sin(2w(t+\delta t)+\phi) - \sin(2wt+\phi))$$

As expected this is zero if $2w\delta t = 2\pi$, but otherwise has a maximum value of $V_o * I_o/(2 * w * \delta t)$ when the sine terms are +1 and -1. The corresponding percentage error in VI is

$$Err\% = 100/(\cos\phi * w * \delta t)$$

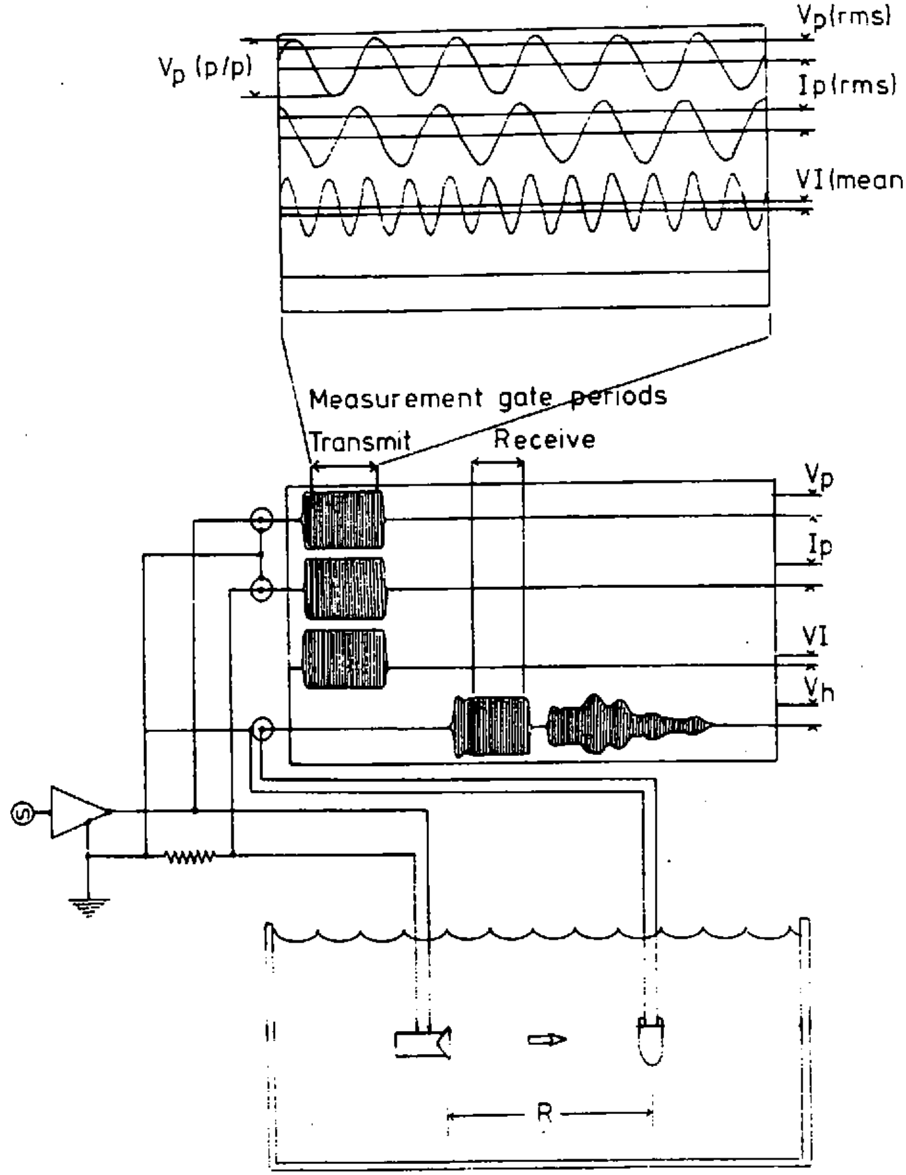
This can usefully be converted to decibels

$$\underline{Err} = 10 * \log(1 + 1/(\cos\phi * w * \delta t))$$

If the error is to kept below 0.1dB the minimum number of cycles $N(= w * \delta t/2\pi)$, over which the averaging should be done is

$$N = 6.83/\cos\phi \approx 7/\cos\phi$$

Similarly a minimum of 7 cycles is seen to be required for the errors in V_p and I_p to be less than 0.1dB.



Test tank, circuit, and oscilloscope display schematic

CALIBRATION AT HIGH POWER OF PULSED ACOUSTIC TRANSDUCERS

Conclusion

With the aid of a multiplying digital oscilloscope, it is possible to measure the mean power absorbtion of acoustic transducers, even within short pulses. This information can be used as follows-

1. To measure the efficiency of non linear transducers at high power levels.
2. To measure the change in phase of the current with power level, and the associated conductance values.
3. To use this data to monitor the onset of nonlinearities, and to correlate this with mechanisms of failure. It will then be possible to set reliable power levels.
4. To use the above data to design matching networks optimised for high power levels.

References

[1] D. Berlincourt, D. Curran., & H. Jaffe "Piezoelectric and Piezomagnetic materials and their function in transducers" in "Physical Acoustics" W. Mason ed. N.Y. Academic Press 1964 Vol 1, part A pp169-270

[2] American National Standards "Proceedures for Calibration of Underwater Transducers" ANSI S1.20 1972

[3] R.J. Urick "Principles of underwater sound" McGraw Hill 3rd Edn 1983

[4] W.R.McLean "Absolute Measurement of Sound without a Primary Standard" J. Acoust. Soc. Am. 12 pp140-146 (1940)